Data Assimilation
and
The Weather Research and Forecast (WRF) Model

Michael McAtee, Al Bourgeois,
Dale Barker, Jerry Wegiel,
John Michalakes

CHSSI Project CWO-6

Overview

- Background
- 3DVAR Description
- Parallelization
- Performance Results
- Future Work

Background

- Importance of initial conditions to the accuracy of Numerical Weather Prediction
- Variational technique the method of choice operational numerical weather prediction centers
- Operational run-time requirements are stringent

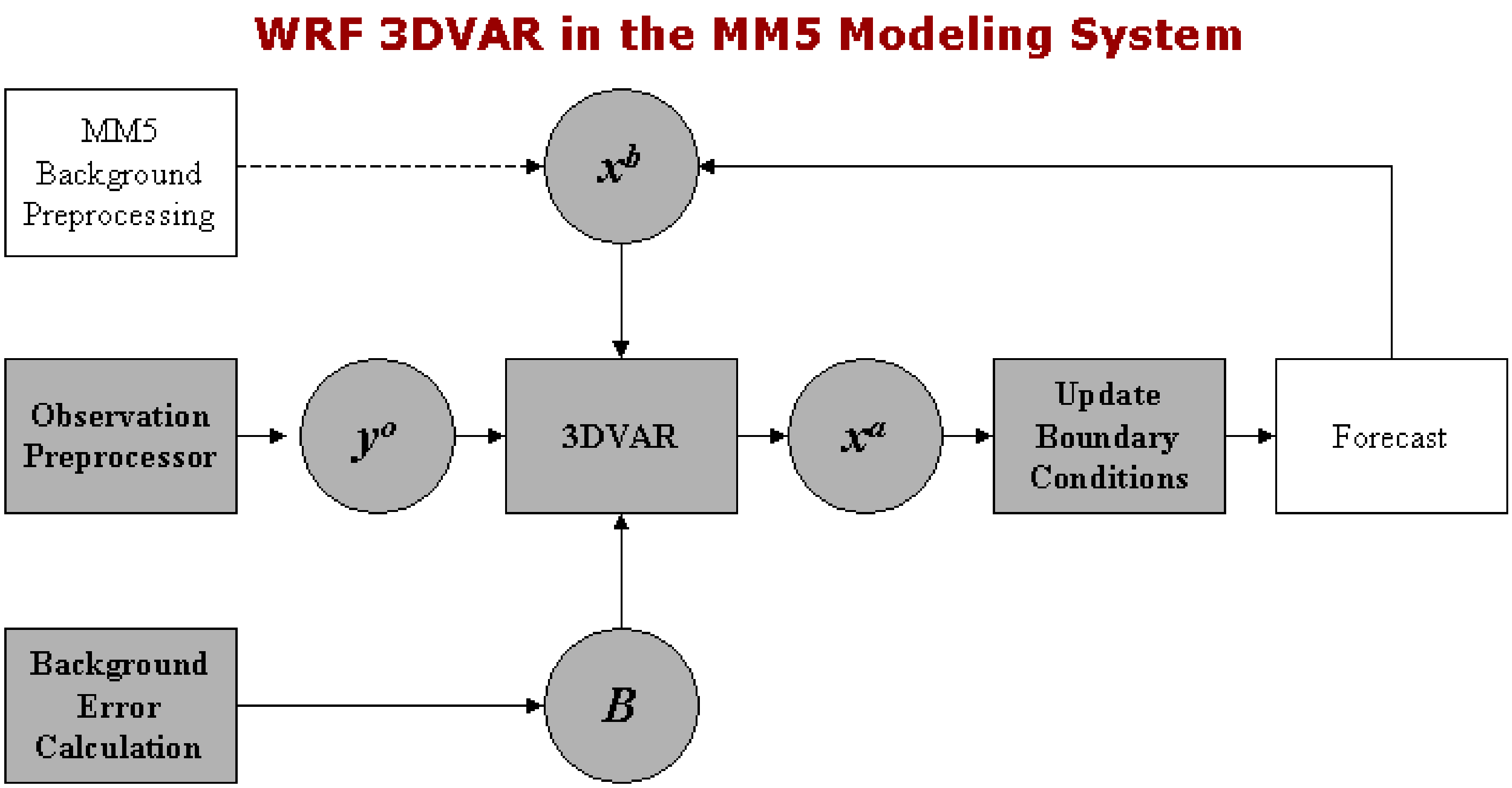
Background

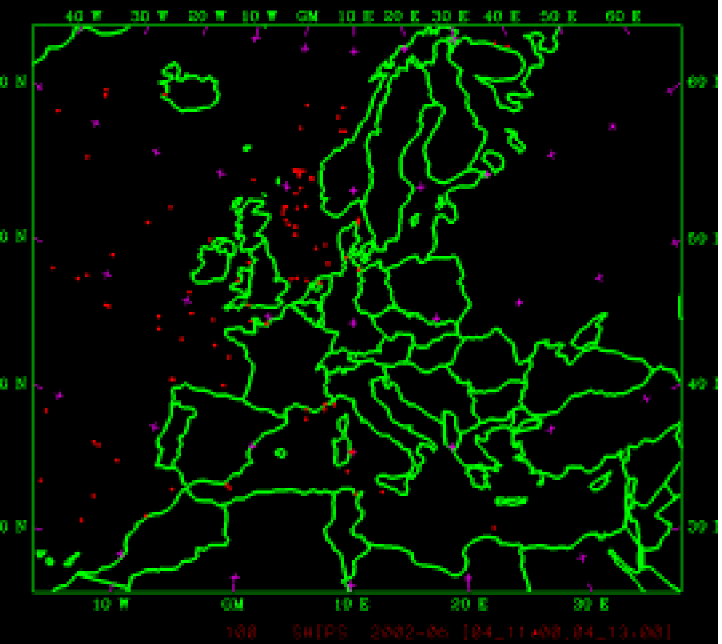
- Serial version of the 3DVAR system originally developed by the NCAR for use with the Penn State/NCAR Mesoscale Model Version 5 (MM5)

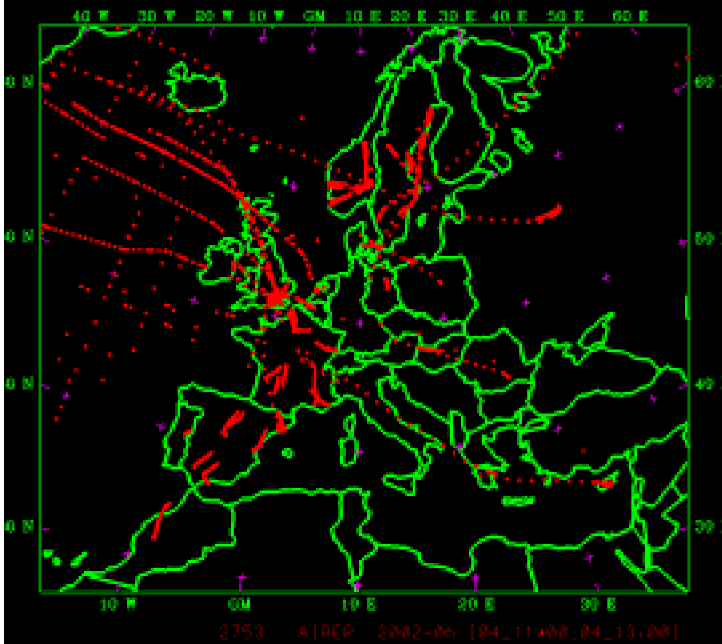
- MM5 3DVAR adopted as the starting point for the parallel WRF 3DVAR

- System currently provides initial conditions for MM5

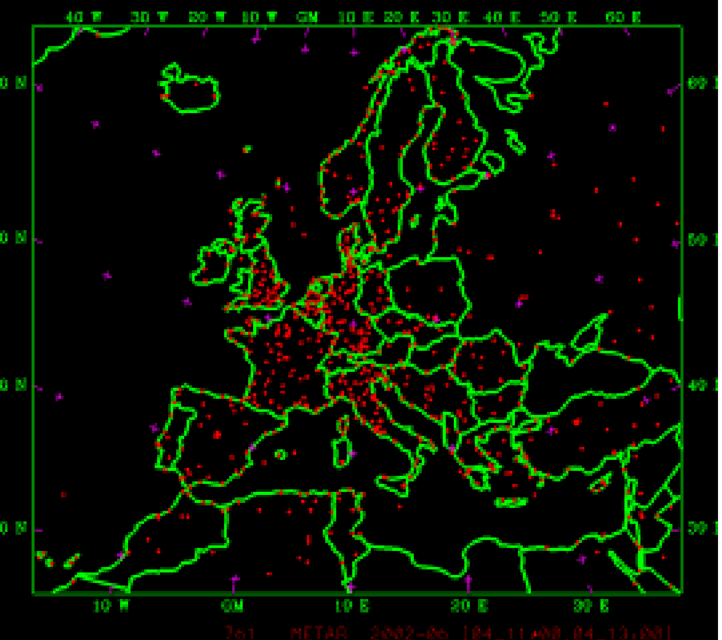
3DVAR Description

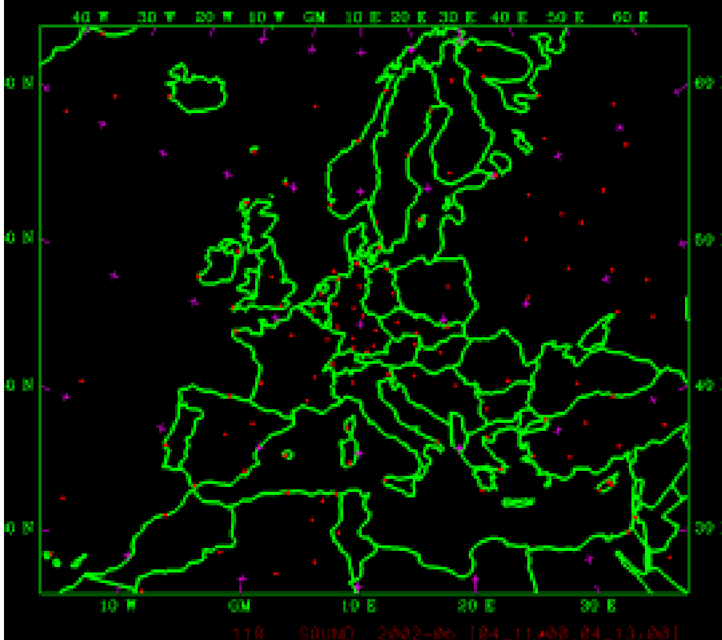


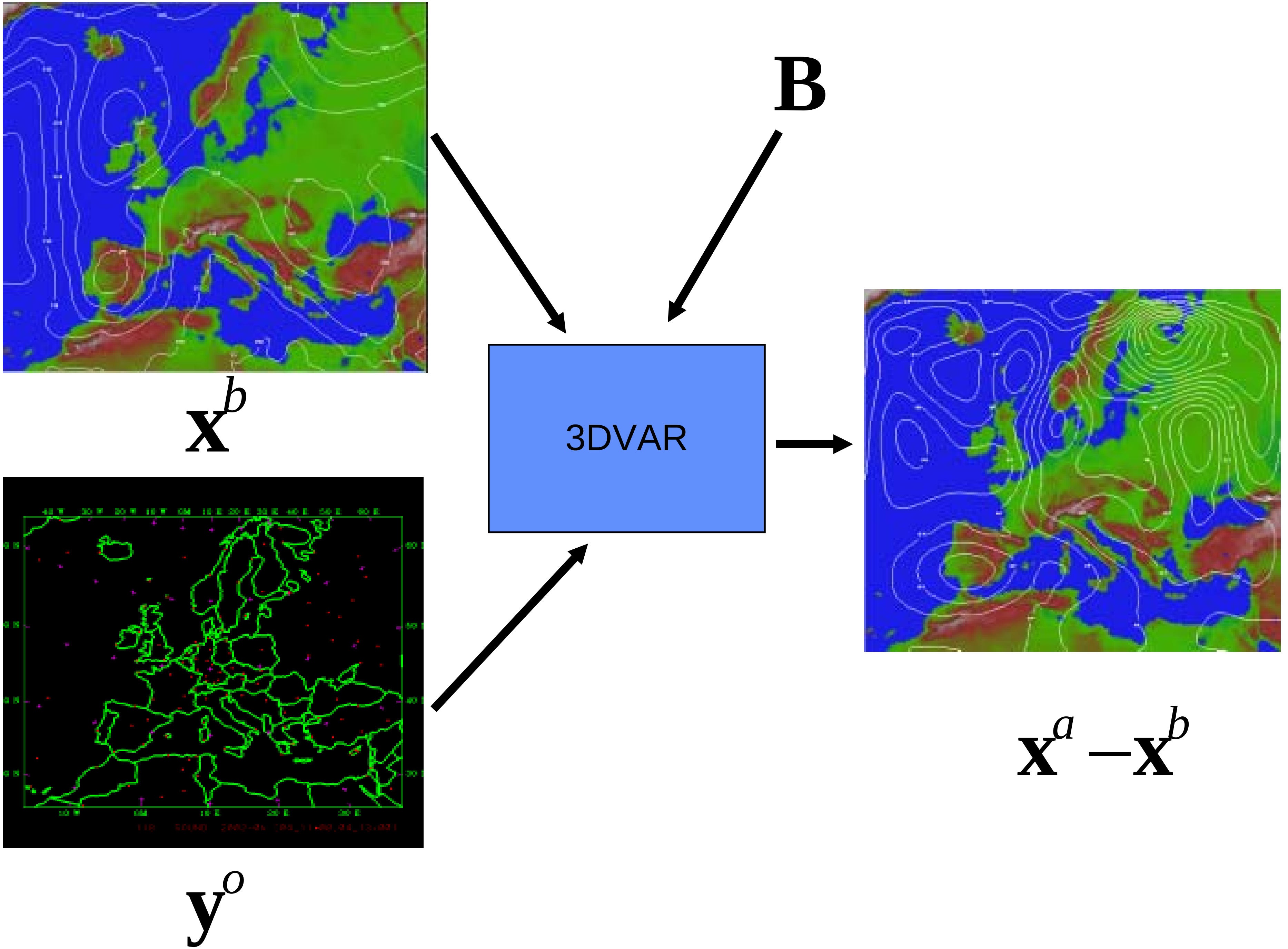




$$\mathbf{y}^{o}$$







B
3DVAR
$\mathbf{x}^b$
$\mathbf{y}^o$
$\mathbf{x}^a - \mathbf{x}^b$

3DVAR
Description

National Center for Atmospheric Research

THE AEROSPACE CORPORATION

$$J(\mathbf{x}) = J^b + J^o = \frac{1}{2}(\mathbf{x}-\mathbf{x}^b)^T \mathbf{B}^{-1}(\mathbf{x}-\mathbf{x}^b) + \frac{1}{2}(\mathbf{y}-\mathbf{y}^o)^T(\mathbf{E}+\mathbf{F})^{-1}(\mathbf{y}-\mathbf{y}^o)$$

y = H**x** where H is the “observation operator”
F = Representivity (observation operator) error
E = Observation (instrumental) error
B = Background error

The problem can be summarized as the iterative solution of the above equation to find the analysis state $\mathbf{x}^{\mathbf{a}}$ that minimizes $J(\mathbf{x})$

3DVAR
Description

- For a model state **x** with n degrees of freedom minimization of $J(\mathbf{x})$ requires $O(n^2)$ calculations

- For a typical NWP model n ~ $10^6 - 10^7$ (number of grid-points times number of independent variables)

- The number of calculations is reduced to O(*n*) by preconditioning the problem via a *control variable* v transform defined by $\mathbf{x}' = U\mathbf{v}$, where $\mathbf{x}' = \mathbf{x} - \mathbf{x}^b$

3DVAR
Description

Using the incremental formulation (Courtier, 1994) and the control variable transform, our previous equations may be rewritten:

$$J(\mathbf{v}) = J^b + J^o = \frac{1}{2}\mathbf{v}^{\mathrm{T}}\mathbf{v} + \frac{1}{2}(\mathbf{y}^{o'} - \mathbf{H}U\mathbf{v})^T(\mathbf{E}+\mathbf{F})^{-1}(\mathbf{y}^{o'} - \mathbf{H}U\mathbf{v})$$

where

$\mathbf{x}' = U\mathbf{v}$

$\mathbf{x}' = \mathbf{x} - \mathbf{x}^b$

$\mathbf{y}^{o'} = \mathbf{y}^o - \mathrm{H}(\boldsymbol{x}^{\boldsymbol{b}})$

H is the linearization of the potentially nonlinear observation operator H

3DVAR
Description

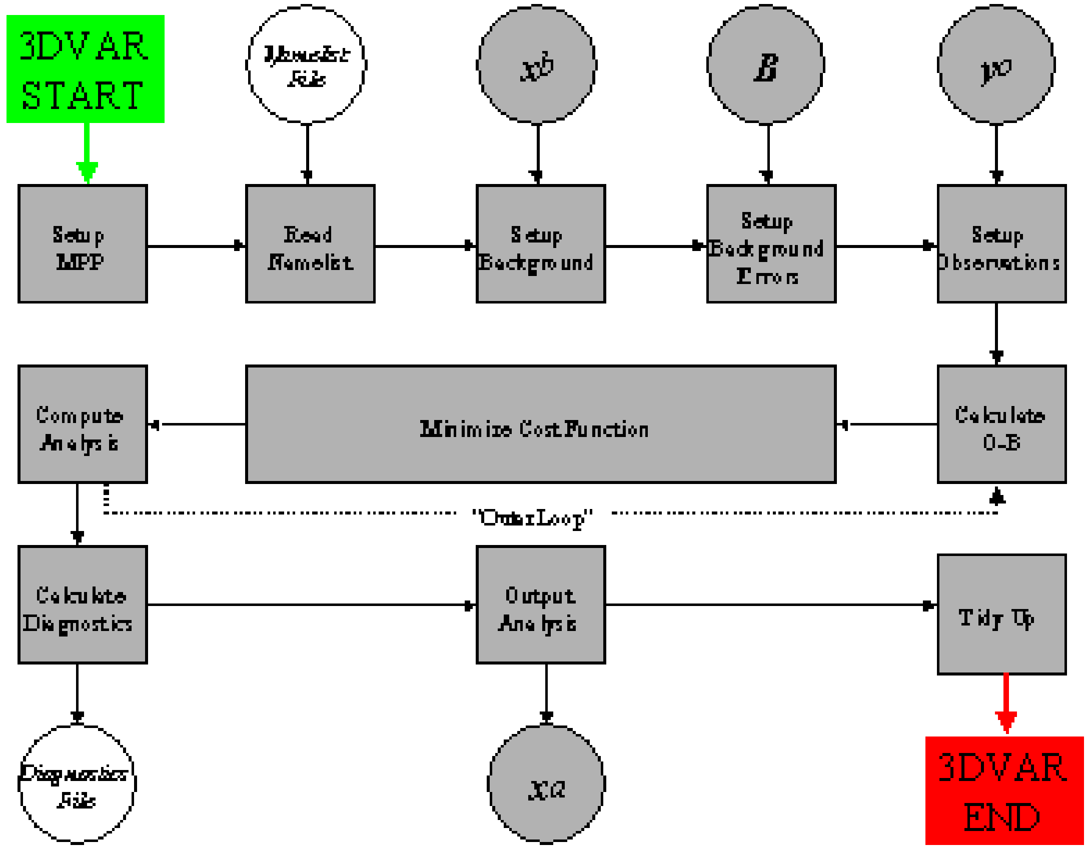
- Use of linear control variable transforms allows the straightforward use of adjoints in the calculation of the gradient of the cost function

- Modern minimization techniques (e.g. Quasi-Newton, preconditioned conjugate gradient) are used to efficiently combine cost function, gradient and the analysis information to produce the “optimal” analysis

3DVAR Description

National Center for Atmospheric Research

THE AEROSPACE CORPORATION



3DVAR
Description

The *minimize cost function* process consists of the following steps:

(1) Apply the conjugate gradient method to find the descent direction in the control variable v and the stepsize to be taken down the descent direction

(2) Calculate the new cost function $J(\mathbf{v})$ and its gradient $\nabla_v J$

(3) Check the norm of $\nabla_v J$ for convergence and iterate steps 1 through 3 until the norm of $\nabla_v J$ is satisfactorily small

3DVAR Description

The bulk of the computation is in step two, which is outlined below:

- Apply the control variable transform $\mathbf{x'} = U\mathbf{v}$ to get from control space to model grid space
- Apply the observation operator $\mathbf{y'} = \mathrm{H}\mathbf{x'}$ and compute the residual vector $\mathbf{y}^{o\prime} - \mathbf{y'}$
- Compute the cost function J and gradient ∇J^o in observation space
- Apply the adjoint transforms to ∇J^o and obtain the total cost function gradient $\nabla_{\mathbf{v}} J$ back in control variable space

3DVAR Parallelization
WRF Framework

- The WRF framework insulates the scientist from parallelism by encapsulating and hiding details that are of no direct concern to the model

- It is organized functionally as a three-level hierarchy, with the low-level model layer protected from architrecture-specific details such as message–passing libraries, thread packages, and I/O libraries

- All management of domain decomposition, processor topologies, and other aspects of parallelism are handled by the framework

3DVAR Parallelization
WRF Framework

- For use with the framework, 3DVAR model subroutines are written to be callable over an arbitrary rectangular subset of the three-dimensional model domain

- The framework ingests the 3DVAR domain size from a namelist file and calculates tile, patch, and memory dimensions for each 2-D decomposition

3DVAR Parallelization Implementation

- The implementation proceeded in three major steps

1. The control variable transform (and adjoint)

2. The observation operator (and adjoint)

3. The conjugate gradient algorithm

3DVAR Parallelization
Control Variable

$$\mathbf{x}' = U\mathbf{v} = U_p U_v U_h \mathbf{v}$$

The individual operators represent in order horizontal, vertical and change of physical variable transforms

U_h is performed using *recursive filters*

U_v is applied via a projection from eigenvectors of a climatological estimate of the vertical component of background error

U_p converts control variables to model variables (e.g. u, v, T, p, q**)** and involves the use of FFTs

3DVAR Parallelization
Control Variable

- The recursive filter and FFT sweeps that are applied in the x and y directions demand data in the entire x and y dimensions, respectively, be known to each processor

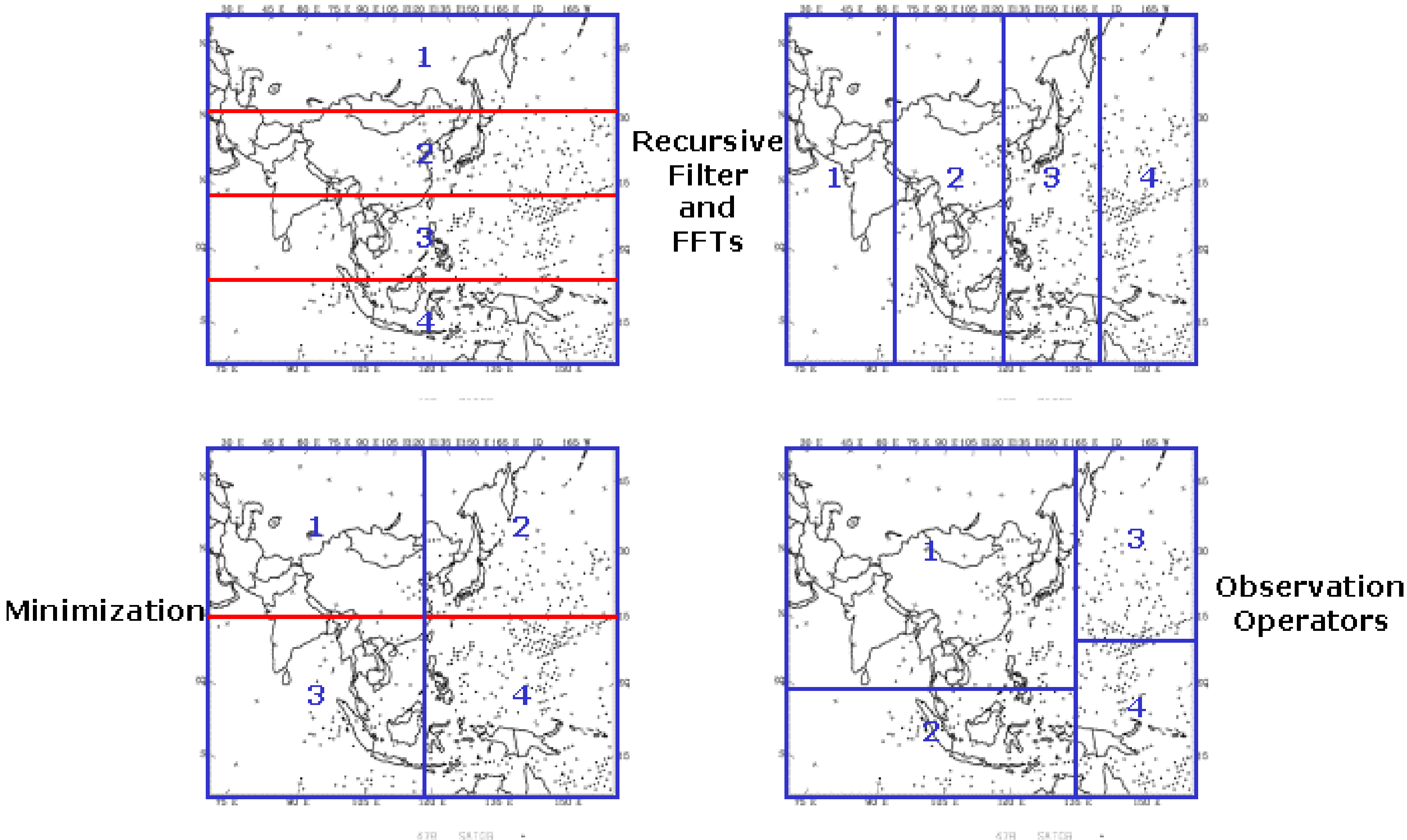
- The framework provides a set of matrix transpose operators for transposing 3D fields across processors

- Applying the recursive filter in each horizontal dimension requires the following sequence of transpose operations:

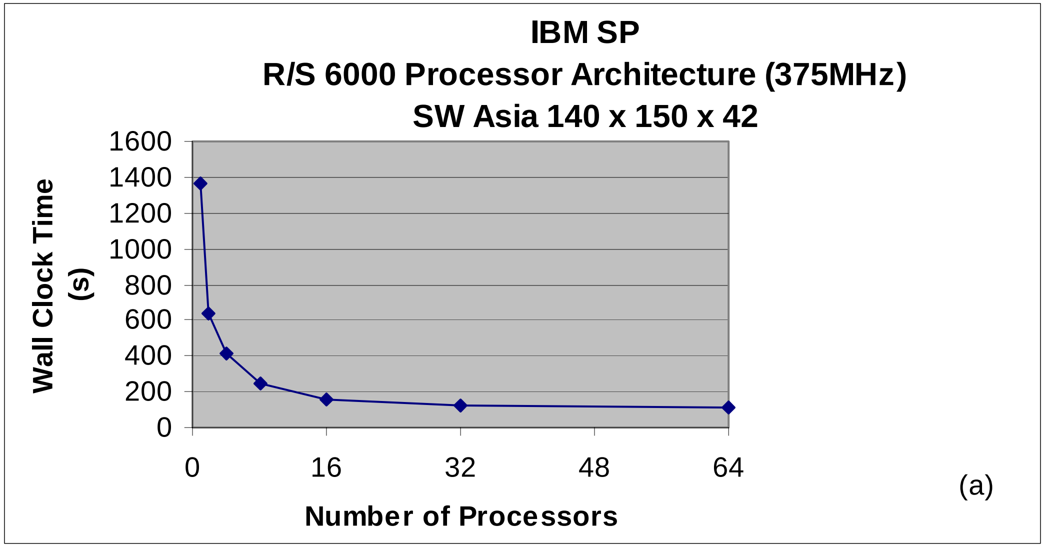
$$(x,y) \rightarrow (y,z) \rightarrow (x,z) \rightarrow (x,y)$$

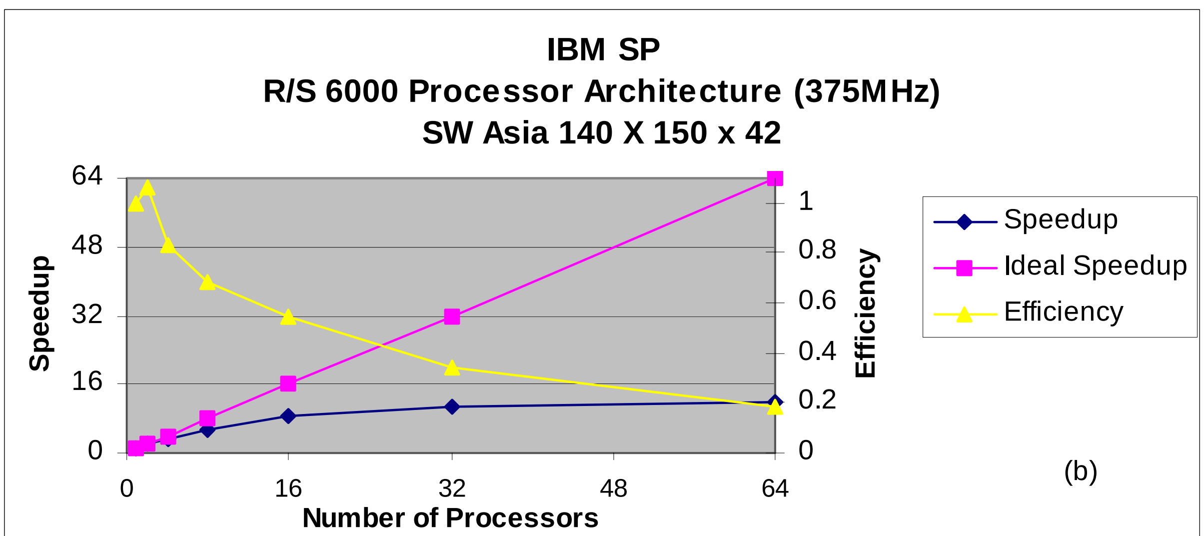
where the notation (x,y) means decomposition over the x and y dimensions.

3DVAR Parallelization



Performance Results





WRF 3DVAR
Future Work

- Performance runs on other platforms (SGI, Fujitsu VPP5000, Linux cluster, and Alpha ES40 cluster)

- Improve memory management